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Emerging Technologies in Ethanol Production

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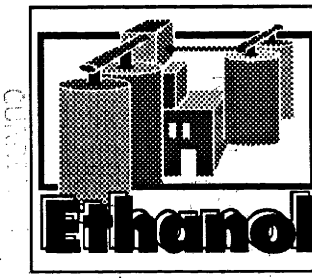


The fuel ethanol industry is poised to adopt a wide range of technologies that would reduce costs at every stage of the production process. Improved enzymes and fermenter designs can reduce the time needed to convert corn to ethanol and lower capital costs. Membrane filtration can allow the recovery of high-value coproducts such as lactic acid. Adoption of these and other innovations in the next 5 years is expected in new ethanol plants constructed to cope with new demand resulting from Clean Air Act stipulations for cleaner burning fuel. Biomass (agricultural residues, municipal and yard waste, energy crops like switchgrass) can also be converted to ethanol, although commercial-scale ventures are limited by current technology. While biomass requires more handling and sorting before conversion, those costs may be offset by the abundance of biomass relative to corn.

The use of ethanol as a fuel for vehicles in the United States grew from insignificance in 1977 to nearly 900 million gallons in 1991. The ethanol industry emerged through a combination of government incentives and new technologies, which enabled large-scale production of ethanol from domestic resources, particularly corn. Growing consumer acceptance of ethanol-blended fuels, incentives to gasoline blenders, and falling costs of production were responsible for the jump in ethanol production. This report examines the likelihood of obtaining further reductions in the cost of producing ethanol from the introduction of new technology.

Technological innovation in the ethanol production process has substantially reduced costs. A shift in production to larger plants and the adoption of energy-saving innovations reduced the processing energy required to produce a gallon of ethanol from 120,000 British thermal units (Btu) in 1981 to an industry average of 43,000 Btu in 1991, resulting in a positive net energy balance (Russo, 1991).[1] (See endnotes at end of report.) The use of improved yeast strains has lowered processing costs. Improvements in enzymes have reduced their cost by more than 50 percent. Such innovations have collectively lowered total production costs from $1.35-$1.45 per gallon in 1980 to less than $1.25 per gallon in 1992.

The construction of new ethanol production plants and the adoption of new technologies at existing plants is likely to lead to further cost reductions. We estimate that over the next 5 years the average cost of ethanol production in the industry will decline by 5-7 cents per gallon because of further technological innovations. Improved yeasts, which tolerate high concentrations of ethanol, can lower energy costs. A system of membranes can recycle enzymes and capture high-value coproducts at many steps in the production process.

Longer term technologies would save approximately 9-15 cents per gallon over present costs. Energy and feedstock savings will result from technology that can convert some of the nonstarch portions of corn to ethanol. Development of microorganisms that speed the process will contribute to long-term savings. Development of markets for coproducts of ethanol production will create additional savings. Cost savings may be less for smaller plants that serve niche markets, or in older plants that must replace inefficient equipment.

The cost of producing ethanol will also be greatly influenced by outside technological advances. Farm technologies that raise corn yields or reduce input costs may lower feedstock costs for ethanol production, as they have in the past. Refinements and new, higher value uses for coproducts are an even likelier source of new revenues and could reduce the cost of ethanol by as much as plant innovations.

Finally, various forms of biomass--agricultural residues, woody or grassy energy crops, or even municipal waste--could supplement corn as an inexpensive feedstock for ethanol production. Although the production of ethanol from biomass is presently constrained by technological difficulties, new developments in this decade may allow ethanol to be produced from biomass at or below the cost of corn-derived ethanol.

The Conversion of Corn into Ethanol

Ethanol is produced from corn by two standard processes: wet- and dry-milling (fig. 1).[2] Wet-milling accounts for about 60 percent of total ethanol production. Dry-milling plants cost less to build and produce higher yields of ethanol (2.6 gallons per bushel vs. 2.5 for wet mills), but the value of coproducts is less.

In each process, the corn is cleaned before it enters the mill. In a dry mill, the milling step consists of grinding the corn and adding water to form the mash. In a wet mill, milling and processing are more elaborate because the grain must be separated into its components. First, the corn is steeped in a solution of water and sulfur dioxide for 24-48 hours to loosen the germ and hull fiber. The germ is then removed from the kernel, and corn oil, a valuable coproduct, is extracted from the germ. The remaining germ meal is added to the hulls and fiber to form the corn gluten feed (CGF) stream. Gluten, a high-protein portion of the kernel, is also separated and becomes corn gluten meal (CGM), a high-value, high-protein (60 percent) animal feed.[3]

In wet-milling, only the starch is fermented, unlike dry-milling in which the entire mash is fermented. The starch is cooked, or liquefied, and an enzyme is added to hydrolyze (break into smaller chains) the starch. In dry-milling, the mash, still containing all the feed coproducts, is cooked, and an enzyme added. In both systems, a second enzyme is added to turn the starch into a simple sugar, glucose (a process called saccharification). Though it usually takes about 24 hours, saccharification in a wet mill may take up to 48 hours, depending on the amount of enzyme used. In modern dry mills, saccharification has been combined with the fermentation step in a process called simultaneous saccharification and fermentation (SSF).

The next step in both processes is the fermentation of glucose into ethanol by yeast (the SSF step in most dry mills). The mash must be cooled to at least 95° F before the yeast can be added. The yeast converts the glucose into ethanol, carbon dioxide, and small quantities of other organic compounds. The yeast, which produces almost as much carbon dioxide as ethanol, ceases fermenting when the concentration of alcohol is around 12 percent by volume.

Distillation, an energy-consuming process, is then required to separate the ethanol from the alcohol-water solution. This step consists of two parts, primary distillation and dehydration. Primary distillation yields ethanol that is up to 95 percent free of water. The dehydration step is necessary to bring the concentration of ethanol up to 99 percent. Several technological options are available for the dehydration step.[4] A small amount of gasoline is added to the ethanol to denature (make unfit for human consumption) it before it leaves the plant. The feed coproducts, CGF and CGM in wet-milling and distiller's dried grains and solubles (DDGS) in dry-milling, must be concentrated in large evaporators, then dried.

Costs of Production Under Present Technology

The cost of producing ethanol depends on a number of factors including the cost of corn, the value of coproducts, the cost of energy and enzymes, the size of the production plant, and the level of technology in the plant. The development and adoption of new technology have been the center of a long-term industry strategy to increase the efficiency of inputs, speed up the production process, and raise the yield of ethanol. Costs of ethanol production are usually divided into three categories: feedstock, capital, and operating costs.

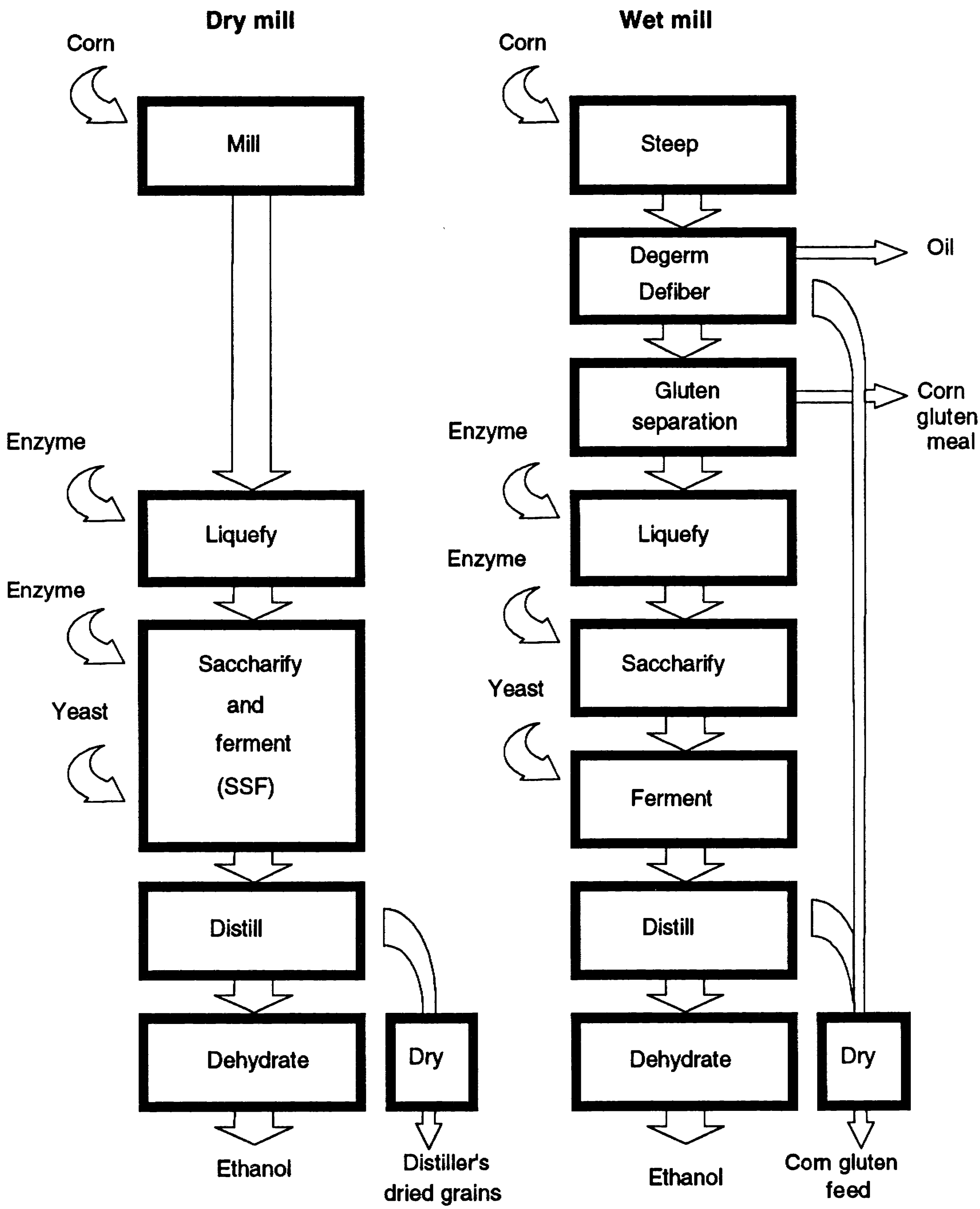
Feedstock Costs

Feedstock cost is a measure of the net cost of the grain from which ethanol is produced. The net corn cost is the difference between the cost of corn and the total revenues received from the sale of coproducts. Over the past 10 years, the net corn cost has been volatile, ranging from 10 to 67 cents per gallon of ethanol. This volatility is mainly due to the large swings in the price of corn, but changes

Figure 1

Flowchart of wet- and dry-milling

Wet-milling separates grain into its components before fermentation, raising costs but increasing production of high-value coproducts.



in coproduct prices have also contributed. Average net corn costs (1981-91) have been 44 cents per gallon of ethanol in a wet mill and 53 cents per gallon in a dry mill. Lower net feedstock costs can be achieved by either lowering the costs of corn or raising the price of coproducts. Technology to lower corn feedstock costs is chiefly aimed at raising the value of coproducts.

Capital Costs

Another component of producing ethanol is capital costs, which include plant modifications, replacement of worn equipment, and a rate of return on the initial investment. The cost of building a new wet-milling plant (excluding energy generation facilities) with an annual production capacity of 100 million gallons is $200-$300 million (LeBlanc and others, 1988), or $2-$3 per gallon of annual capacity. The cost of building a dry-milling plant is considerably less because the capital-intensive steps of steeping, degerming, and defibering are not performed. The estimated capital cost of $0.43 to produce a gallon of ethanol in a state-of-the-art plant (table 1) is based on an initial investment of $2.25 per gallon of annual capacity and a 15-percent rate of return to investors.

In both dry-milling and wet-milling plants, high capital costs are associated with steps where the process slows or requires special equipment (fig. 2). For example, the steeping step in wet-milling requires large containing vats to ensure sufficient flow to the next stage. Technological innovations that speed up the process or replace expensive equipment are therefore likely to lower capital costs. The total value of capital equipment in a wet-milling plant is higher than in a dry-milling plant. The primary capital expenditure in a wet-milling plant, which accounts for the sizable cost differences, is recovery equipment for removing the germ, oil, and fiber from the corn kernel. In dry-milling plants, nearly half of capital expenditures are for equipment to process coproducts.

Operating Costs

Operating costs constitute the final component of production costs and include energy, enzymes, labor, management, taxes, and insurance. Many technological innovations have focused on reducing operating costs by raising the efficiency of inputs,

Table 1--Average ethanol production costs[1]

Cost category	Cost
	Dollars/gallon
Feedstock[2]	0.44
Capital[3]	.43
Operating	.37
Total[4]	1.24

[1] A state-of-the-art wet-milling plant with cogeneration of steam and electricity and energy-efficient dehydration. Most ethanol output (1992) is from such plants.
[2] Net corn costs are based on industry average net corn costs, 1981-91. Coproduct credits are reported in the *Sugar and Sweetener: Situation and Outlook Reports.*
[3] Capital and operating costs are updated from LeBlanc and others (1988) and verified with industry sources.
[4] The estimated cost of production of ethanol is $1.08-$1.95 per gallon (see U.S. Department of Energy and others, 1992). The lowest cost figure may, however, be difficult for producers to achieve because the final cost depends on the prevailing corn price, and because savings in one area, such as capital costs, may come at the expense of savings in another area, such as energy.
Source: Industry contacts (see list of Individuals and Organizations Contacted).

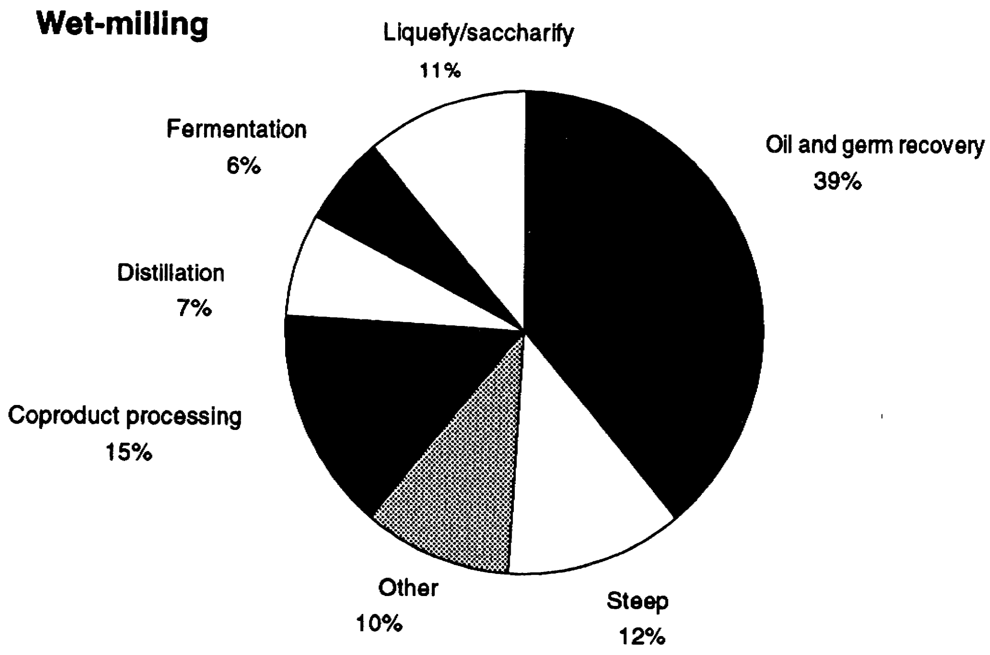
particularly energy. Energy is the greatest operating cost, so innovations that conserve energy have been among the first adopted in the industry, and have accounted for most of the savings in the last 5 years. Most large ethanol plants now receive steam and electricity at low cost from cogeneration facilities that simultaneously produce both. The industry also has reduced energy costs by adopting more efficient means of alcohol dehydration. Lower membrane costs and improved technology may make pervaporation (the use of a semipermeable membrane) an economical option. However, large savings in energy costs are not likely because the present level of efficiency is close to optimal.

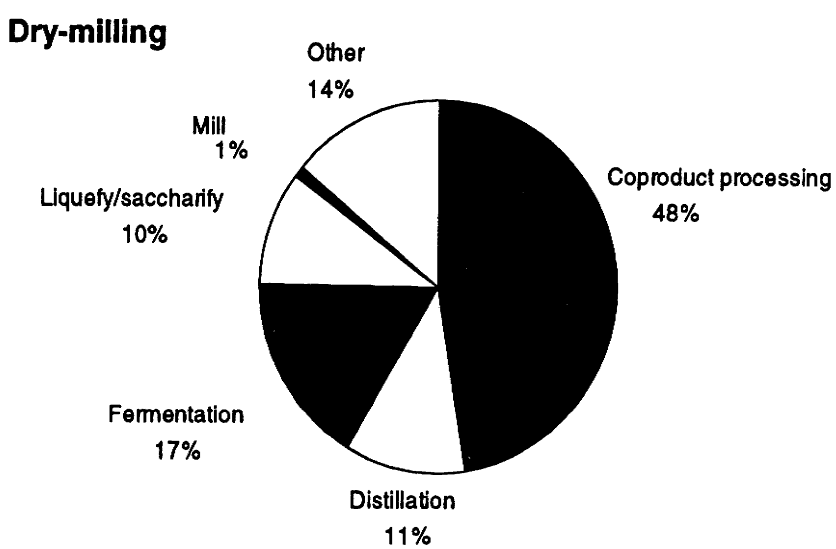
The second largest operating cost is the cost of yeast and enzymes. Although these costs have fallen considerably in the past few years, particularly for enzymes, research may further lower the cost of propagating these organisms or reduce the volume needed. Many plants now use computers to control the production processes, reducing supervision and lowering labor costs.

Figure 2

Capital costs for wet- and dry-milling plants

Wet-milling equipment is more costly than that for dry-milling due to more extensive recovery of high-value coproducts (including oil and germ recovery).





Note: Sizes of pie charts reflect total capital costs.
Source: Kelm, 1984.

An additional source of savings from technological innovations is improvement in the yield of ethanol.[5] Potential yield improvements could come from more complete conversion of starch to sugar and fermentation of the sugars, more efficient recovery of the ethanol, or the conversion of currently unavailable portions of the feedstock. As yields rise, each gallon of ethanol may be produced from a smaller amount of feedstock, with lower capital investment and lower operating expenses. Therefore, even small improvements in yields create substantial savings in overall costs.

Production Cost Savings from New Technologies

A variety of cost-saving innovations will be available to the ethanol industry for use in the next 2-5 years. Adoption of these innovations, however, depends on an expanding industry that invests in new capital equipment. An estimate of the total cost savings of a new 1996 plant, employing a likely combination of these innovations, over a present state-of-the-art plant is 5.4-7.3 cents per gallon of ethanol produced. In the longer term, still more innovations are likely to move from experimental stages to the plant. In the long term (5-10 years), further cost-saving technologies may save an additional 3.5-8.1 cents per gallon (table 2).

Assessment of Near-Term Technologies

Innovations likely to be adopted in the near term by the ethanol industry focus on speeding the process time and lowering operating costs (fig. 3). The high estimate for each innovation is a technical upper limit to possible cost savings; the low estimate is based on industry sources (see list of Individuals and Organizations Contacted).

Gaseous injection of sulfur dioxide and the use of special corn hybrids. The application of sulfur dioxide (SO_2) in gaseous form and the use of corn hybrids that have shorter steeping times greatly reduce the time corn must spend steeping in large tanks. This time savings means smaller or fewer tanks will be needed to produce the same amount of ethanol. New plants that adopt gaseous injection may save 1.3-1.7 cents per gallon of ethanol in capital costs when refinements to the process are completed.

Special corn hybrids also shorten steeping time, but are expected to sell at a premium to the type of corn normally used in wet-milling. With an assumed 2-cent-per-bushel premium, use of special hybrids could save 1-1.8 cents per gallon in capital costs. These capital cost savings are available only in a new wet-milling plant because older plants have already invested in steeping tanks and dry-milling does not involve the steeping step.

Membrane filtration. Another source of savings in capital costs is a shortening of fermentation time, which allows the use of smaller fermenters. One experimental fermenter design (Simms and Cheryan, 1992) would allow water and ethanol to penetrate a membrane, while trapping the starch and yeast in the fermenter. With the yeast retained, fermentation can proceed continuously at a fraction of the conventional 40-50 hours. As the fermentation time decreases, however, the concentration of the ethanol also decreases. Energy costs per gallon of ethanol rise because more energy is required to distill a more dilute ethanol solution. Nonetheless, with efficient distillation, continuous fermentation with membranes could produce significant capital cost savings for a new plant in the near term.

Membranes also are likely to be used in the saccharification stage to retain enzymes and starch, while allowing glucose and water to pass through. By reducing saccharification time in wet-milling to 10-15 hours and enzyme requirements by a factor of 10, this process could reduce operating costs by 1.2-1.5 cents per gallon of ethanol and achieve small capital cost savings in a new plant. Many wet mills are expected to install membrane systems in the saccharification step because of operating cost savings.

The development of low-cost reliable membranes may allow many plants to recover high-value coproducts and lower operating costs at many points in the production process. The energy and equipment needed to dry the coproducts could be significantly reduced by running liquid components through a microfiltration unit to absorb excess water. High-value coproducts such as lactic acid may also be recovered and concentrated through a system of membranes. The use of membranes gives plants a greater degree of control over the

Table 2--Model plants of 1996 and 2001 and associated production cost savings

Bold type below shows technologies not currently used commercially, but expected to be adopted during the phase indicated.

Model plant of 1996 (near-term technology)		Model plant of 2001 (long-term technology)	
Innovations		*Innovations*	
Cogeneration		Cogeneration	
Steeping with gas injection of sulfur dioxide		Steeping with gas injection of sulfur dioxide	
Membrane saccharification		Membrane saccharification	
Fermentation:		Fermentation:	
High-tolerance yeast		High-tolerance yeast	
Yeast immobilization		Yeast immobilization	
		Bacterial fermentation	
Dehydration:		Dehydration:	
Azeotropic distillation		Azeotropic distillation	
Corn grits adsorption		Corn grits adsorption	
		Pervaporation	
		Cellulosic conversion of corn fiber	
Cost savings over present[1]		*Cost savings over present*	
Feedstock[2]	\$0.010 - \$0.014	Feedstock	\$0.010 - \$0.047
Operating	\$0.025 - \$0.032	Operating	\$0.027 - \$0.034
Capital[3]	\$0.019 - \$0.027	Capital	\$0.052 - \$0.073
Total	\$0.054 - \$0.073	Total	\$0.089 - \$0.154

[1] The high estimate for these combinations of technologies is based on the technical upper limit to possible cost savings from individual technologies; the low estimate incorporates more practical obstacles to implementation, and is probably more realistic.
[2] Savings from coproduct development are potentially large but speculative, so are not included.
[3] Older plants will be unable to take full advantage due to previously purchased capital equipment.

production of alcohol and allows a greater degree of separation among the various parts of the product stream. These benefits may reduce operating costs at many segments of the plant and curtail capital costs for plants designed to include membrane systems.

Other improvements. Another method of lowering operating costs is the improvement of the fermenting organism. The development of yeasts that can work in higher ethanol concentrations (Maiorella and others, 1984) could lower the energy costs of distilling alcohol by 0.8-1.2 cents per gallon of ethanol.

One alternative fermenter design could raise ethanol yields during the fermentation step. This design immobilizes yeast in beads suspended in a gel. A continuous stream of glucose is fermented as it passes through the gel (Nagashima and others, 1984), speeding the fermentation process and raising ethanol yields. If these yield increases are realized in a new plant, total cost savings will be 2.0-2.7 cents per gallon of ethanol. Although problems with sustaining yeasts while immobilized remain, yeast immobilization reactors should be available in the near term.

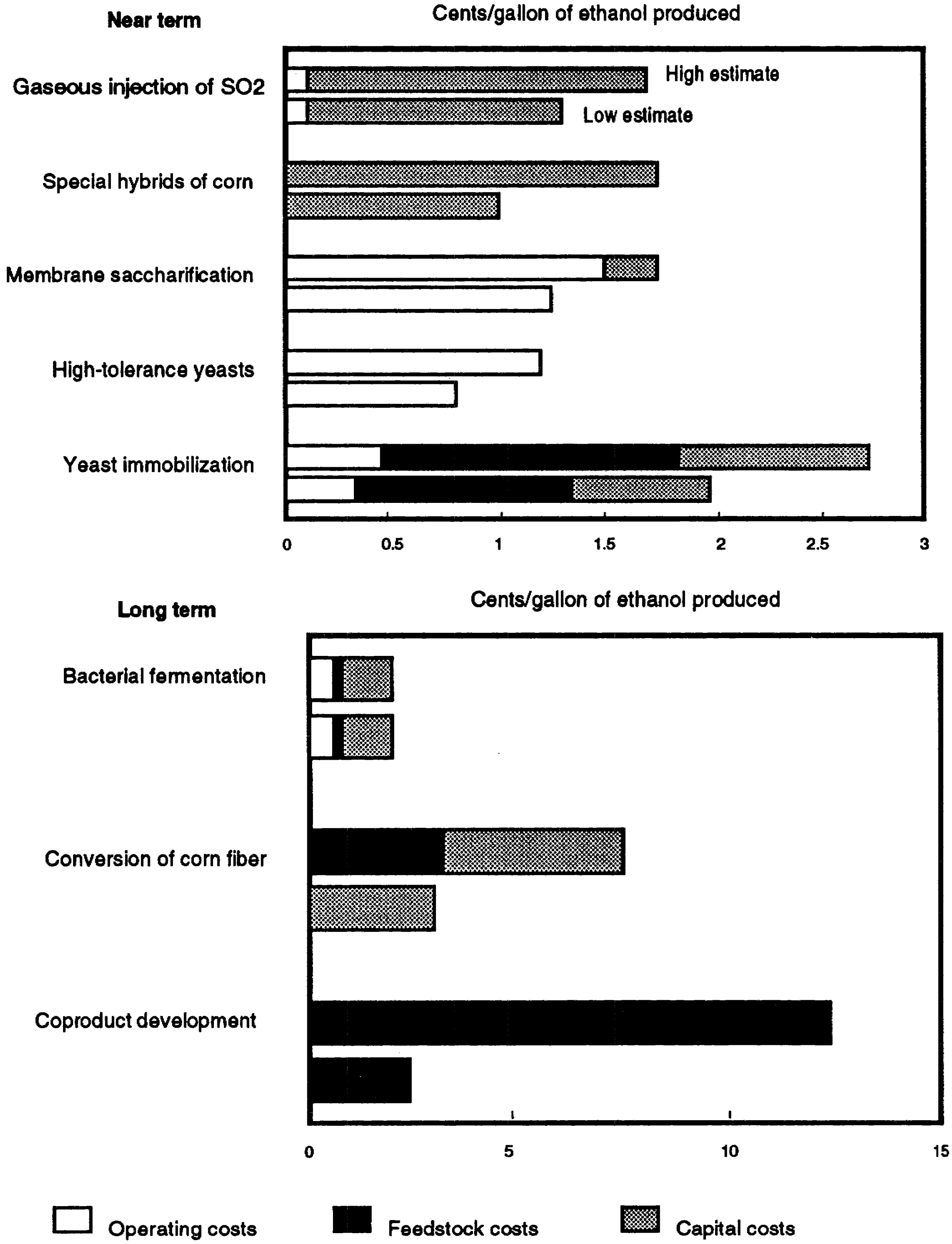
Assessment of Long-Term Technologies

Technologies that may be incorporated into plants in 5-10 years include bacterial fermentation, conversion of corn fiber to ethanol, and coproduct development (fig. 3). While bacterial fermentation is expected to

Figure 3

Production cost savings from new technologies, near and long term

High estimates reflect maximum savings that can be achieved in theory. Low estimates reflect more likely practical savings to be realized in real-world applications.



Source: Estimates are based on industry and academic sources. See list of Individuals and Organizations Contacted.

reduce feedstock costs, its primary contribution will be in savings on capital equipment. Conversion of corn fiber will save on capital equipment and also contribute to feedstock savings. Coproduct development will lower net feedstock costs by raising the value of coproducts.

Bacterial fermentation. A possible substitute for improved yeast is a wholly different fermentation organism. The bacterium *Z. mobilis*, in laboratory testing, has quickened fermentation, raised alcohol yields slightly, and allowed fermentation at higher temperatures (Busche and others, 1991). Production cost savings from such performance could be as high as 2 cents per gallon. Most of the reduction would be in capital costs because the savings from reduced capacity requirements per bushel of feedstock would outweigh the cost of the new equipment needed (Texeira and Goodman, 1991). Less cooling would be required, reducing energy costs, and some feedstock savings would result from greater conversion efficiency. The *Z. mobilis* bacteria are less stable than yeast and more sensitive to changes in pH and temperature, but these problems may be overcome in the next 5 years.

Conversion of corn fiber to ethanol. Current ethanol recovery is approaching the theoretical limit available from the starch portion of the kernel. Converting the hull and other fiber portions of the kernel into ethanol could raise ethanol yields from 2.6 to nearly 3 gallons per bushel. At the same time, the quality of the feed coproduct would improve because, due to fiber loss, the protein content would be higher. The quantity of feed coproducts, however, would fall. Problems may also emerge in drying the coproducts without the fiber acting as a binder for the other components.

Conversion of corn fiber is likely to lower feedstock costs and capital costs. Net corn costs would be reduced by raising both ethanol yield and the value of the coproduct. Capital costs are lower because of higher yields, even though fiber conversion requires unique capital equipment and an increase in distillation capacity. Total savings are expected to be 3-7.5 cents per gallon.

Coproduct development. Coproduct sales are potentially the most profitable area of research. The value of ethanol is closely tied to the price of other energy sources, the price of the feedstock is largely dictated by its alternate uses, and production cost reductions are limited by the physical processes involved in the conversion to ethanol. Revenues from coproducts are not bound by these restrictions.

Some research on coproduct recovery focuses on using semipermeable membranes to remove small quantities of valuable products from the corn-refining stream. One such coproduct is lactic acid, produced unintentionally during fermentation. (In the long run, however, it may prove more economical to produce lactic acid in a separate fermentation.) High-value, low-volume coproducts, such as citric acid or sorbitol, may be removed as more sophisticated membrane technology becomes available.

Coproduct research also focuses on high-value uses of carbon dioxide, produced in quantities almost equal to ethanol, but currently sold for less than 1 cent per pound. Researchers have discovered a bacterium that converts carbon dioxide and hydrogen into acetic acid (Wood, 1991). Converting the carbon dioxide from the production of a gallon of ethanol into acetic acid is estimated to cost around $0.75 and produce about 4.3 pounds of acetic acid, which at current prices would sell for more than $1.50. If acetic acid were produced on a large scale, its price would probably fall, but this process illustrates, nonetheless, the potential for achieving sizable savings through the further development of coproducts. There are several other possibilities for industrial use of carbon dioxide (Myers, 1992). It is difficult to predict which coproducts will eventually emerge as most profitable, but in the long term, savings from all of them could be as large as savings from plant innovations.[6]

Industry Expansion

A great deal of additional production can be coaxed out of existing facilities. However, for production to increase sufficiently to meet the demand for oxygenated (cleaner burning, as stipulated by the Clean Air Act) fuels, much of the increase will have to come from newly constructed facilities. New plants will be able to employ new technology more easily than older plants, improving the industry's overall efficiency. The older plants will be limited to "plug-in" or modular technologies that do not require redesigning the entire plant.

To take advantage of economies of scale, new wet-milling facilities will probably have an annual capacity of at least 100 million gallons. Building new facilities will introduce state-of-the-art technologies at a faster rate than they have been adopted in the past. This acceleration will improve the industry's overall efficiency.

Economies of scale for dry mills may begin to level off at about 50 million gallons of annual capacity. Dry mills can be built economically on a smaller scale and fit operations that can feed the coproduct to livestock without drying. Increases in other niche markets are also possible. Lactose from cheese whey, for example, has been successfully fermented to ethanol, solving a disposal problem and adding to the product line at the same time.

The Conversion of Biomass into Ethanol

A jump in ethanol production through the conversion of corn kernels is likely to be constrained by a number of factors: the relatively high cost of corn, which has many alternate uses; limited markets for coproducts such as corn gluten feed and dried grains and solubles; and competition for land suitable for corn cultivation. A doubling of ethanol production from corn would require approximately 350 million additional bushels of corn each year, putting upward pressure on the price of corn and doubling the supply of coproducts. Other food crops considered as a feedstock for ethanol production, such as potatoes and sugarcane, are also expensive because of their high value as human food products. These restrictions do not apply, however, to the organic material called biomass, which is available as a byproduct of agricultural production and as a waste material.

Biomass includes agricultural residues, waste streams from agricultural processing, municipal solid wastes, yard and wood wastes, and crops grown expressly for their energy content. These materials cost much less than corn and are more abundant. Conversion of waste materials and agricultural residues into ethanol could produce up to 3.8 quads (1 quad = 10^{15} Btu) of energy each year. Crops grown expressly for energy content on excess cropland could annually produce 11.4 quads of energy. Together, these sources of energy would account for half of the total annual consumption of energy in the U.S. transportation sector (Lynd and others, 1991).

Technological Barriers and Opportunities

Technology for converting biomass into ethanol has until recently been unproven and too costly for commercial-scale ventures. Although simple sugars are ultimately fermented to form ethanol from both corn and biomass feedstocks, the sugars in biomass are more tightly bound in long chains, and some simple sugars are different from the sugars in corn. A kernel of corn is composed primarily of starch, which is readily reduced into glucose, a sugar that can be efficiently fermented by yeast into ethanol. Most biomass is composed of cellulose, hemicellulose, lignin, and ash. The cellulose and hemicellulose fractions are made up of long chains of six-carbon sugars (glucose) and five-carbon sugars. The cellulose portion ranges from 30 to 50 percent of total weight, hemicellulose from 25 to 35 percent, and lignin from 10 to 30 percent, depending on the feedstock. Lignin cannot be converted into ethanol, but can serve as an energy source and combustible fuel for the conversion of cellulose and hemicellulose into ethanol.

A biomass conversion plant would differ from the conventional wet or dry mill first in the prehandling and sorting steps (fig. 4). These steps vary considerably depending on the biomass feedstock. For example, processing municipal solid waste requires a more complicated and costly sorting procedure than processing agricultural residues. The biomass conversion process also varies from conventional corn processing because of the need to break down cellulose and to ferment five-carbon sugars.

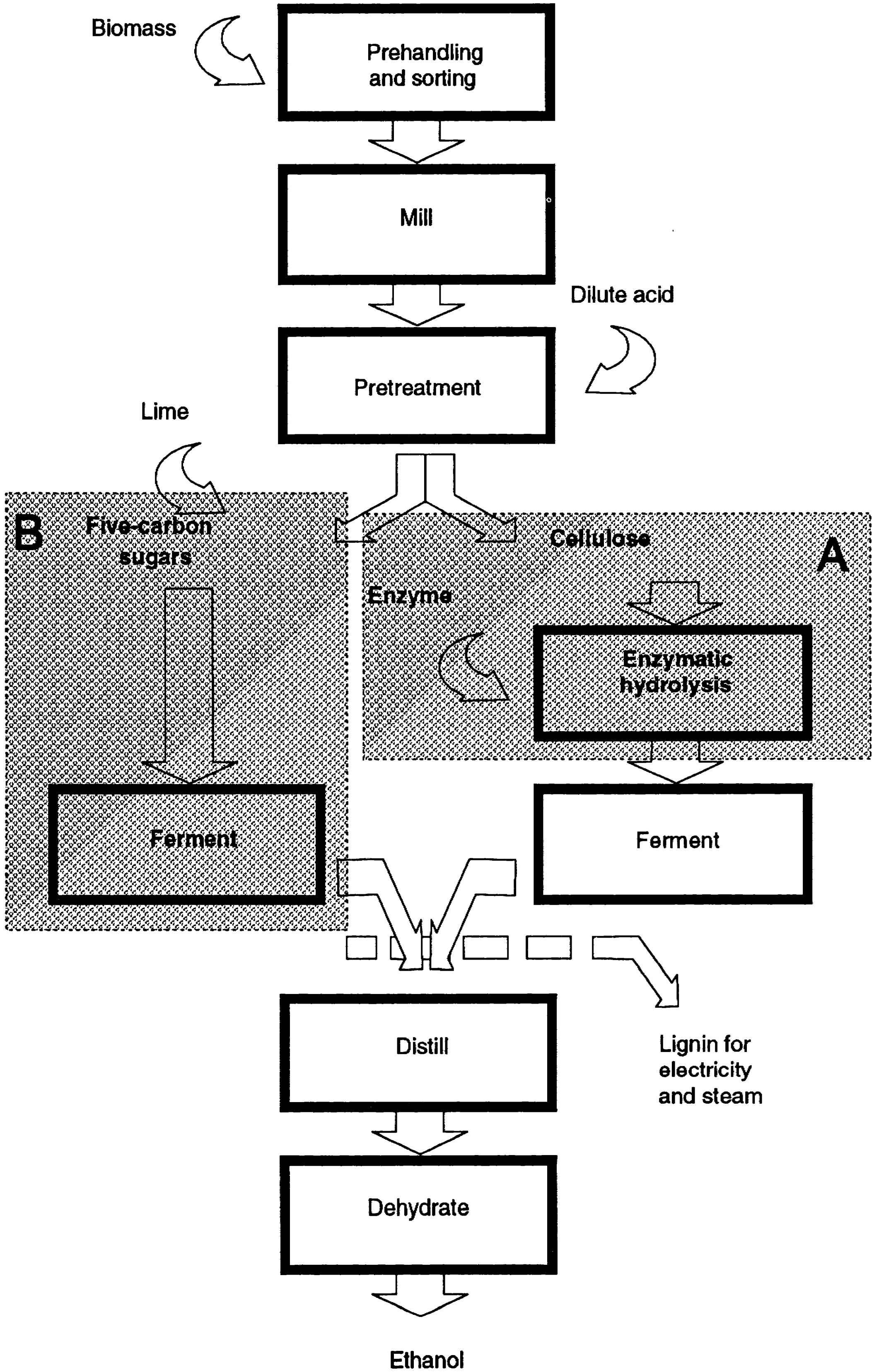
After sorting, the feedstock material is ground in a mill and goes to the pretreatment stage where dilute acid is used to break down the hemicellulose into five-carbon sugars. The five-carbon sugars are then fermented separately. The cellulose is broken down into glucose through enzymatic hydrolysis before being fermented in the usual way. Lignin is a byproduct of biomass conversion that has potential industrial uses. Current plant designs use lignin as a source of electricity and steam.

The two technological barriers to biomass conversion have been the lack of an efficient

Figure 4

Flowchart of yard waste biomass processing plant

Biomass conversion requires a separate process to break down complex five-carbon sugars.



method for hydrolyzing (converting) cellulose into glucose and the lack of an effective organism for fermenting five-carbon sugars. Although both corn starch and cellulose are composed of chains of glucose, the complex structure of cellulose makes the complete separation of all the glucose molecules extremely difficult. Concentrated mineral acids, such as sulfuric acid, have been used to break the bonds between glucose molecules. The hydrolysis of cellulose through the use of acids, though rapid and efficient, also has significant drawbacks. Acid hydrolysis requires expensive containment and recovery systems to keep acid costs and equipment corrosion to a minimum. Furthermore, the highly reactive nature of acid hydrolysis reduces some glucose into useless and possibly toxic byproducts.

An alternative process combines a chemical pretreatment of cellulose with an enzymatic hydrolysis (fig. 4, area A). Enzymes capable of hydrolyzing cellulose are produced in large quantities from microbial sources. The enzymes, which act as catalysts, operate slowly and have been more expensive than acids. On the other hand, glucose yields from enzymatic hydrolysis can approach 100 percent of the theoretical yield, and advances in genetic engineering promise to lower the cost of enzymes. When enzymatic hydrolysis is employed after a pretreatment step, the hydrolysis and fermentation stages of ethanol production can be combined. This process, another form of SSF, raises productivity by allowing the fermenting organisms to consume simple sugars such as glucose as soon as they are separated by the enzymes. Enzymatic hydrolysis appears to be the process through which the goal of cleanly and cheaply converting cellulose into glucose is most likely to be achieved.

The remaining technical barrier to biomass conversion has been the lack of an organism to ferment the five-carbon sugars that result from the hydrolysis of hemicellulose (fig. 4, area B). Unlike cellulose, hemicellulose hydrolyzes easily with a mild pretreatment into a variety of five-carbon sugars. Common strains of yeast, however, either cannot ferment five-carbon sugars or cannot tolerate high concentrations of ethanol. The inability to convert such a large portion of biomass into ethanol makes production economically infeasible. Advances in genetic engineering, however, have largely overcome this barrier. Genes that instruct other organisms to ferment both five- and six-carbon sugars have been introduced into *E. coli*, a bacterium present in the human digestive system. The resulting organism is capable of fermenting both glucose and five-carbon sugars with a high productivity and with fermentation yields that match those of common yeast strains (Ingram and others, 1991). Further genetic improvements to fermenting organisms may reduce enzyme requirements for the hydrolysis of cellulose and raise fermentation yields.

A number of problems for biomass conversion remain. Pretreatment systems must be developed that economically allow high yields of sugar during hydrolysis. Also, because biomass feedstocks are much more diverse than those for corn-derived ethanol, the effects of heterogeneous feedstocks must be closely examined. Finally, it must be demonstrated that the fermenting organisms are stable during fermentation and environmentally benign.

Costs of Production

The technology for converting biomass into ethanol is at a stage in which working production plants are being designed for near-term construction. Operating and capital costs for prospective biomass conversion plants (table 3) are not much higher than operating and capital costs for very large and efficient wet- and dry-milling plants. Biomass conversion plants are assumed to have optimized production parameters based on the experience of earlier plants of similar design; costs are typical of fifth or tenth plants, rather than of the first pilot plant. No biomass conversion plant has been constructed yet, so cost estimates are speculative. Also, biomass provides its own energy source for ethanol conversion in the form of lignin, which can be burned in a boiler to provide steam and electricity, reducing costs relative to corn conversion. Both biomass conversion plants (table 3) are capable of providing all their power using lignin and even generating an electricity credit if access to local utilities is available. Energy expenditures are the largest operating cost in wet- and dry-milling plants.

Finally, biomass conversion plants will differ from corn wet- and dry-milling plants in the front end of the plant, where sugars are extracted from different feedstocks. Biomass is a relatively bulky feedstock,

Table 3--Cost estimates for two biomass conversion plants

Cost category	Plant 1 (10 million gallons/year)	Plant 2 (60 million gallons/year)
	Dollars per gallon	
Operating costs	0.481	0.339
Labor	.087	.027[1]
Fuels	.012	___[2]
Nutrient, boiler chemicals, acid	.100	.141
Enzymes	.115	___[3]
Supplies and materials	.035	___[4]
Maintenance	.058	.066
Overhead	.035	.072
Tax and insurance	.039	.033
Capital cost	.390	.484[5]
Operating and capital costs	.871	.823
(Electricity credit)	N.A.	-.071
(Waste disposal cost)	N.A.	-.007

N.A. = Not available.
[1] Lower cost is a result of economies of scale (compared with plant 1).
[2] Power provided by lignin, produced during biomass conversion.
[3] Plant 2 produces enzymes for the hydrolysis of cellulose.
[4] Included in the nutrient, boiler chemicals, acid category.
[5] Higher productivity due to faster rates of reaction lowers cost in plant 1, while enzyme-producing equipment raises cost in plant 2.
Source: Costs for plant 1 are obtained from Bioenergy International and for plant 2 from the National Renewable Energy Laboratory.

so a conversion plant requires an extensive handling facility for processing delivered biomass into a usable form. Some feedstocks require more processing than others. Extensive sorting and filtering is required to separate the fermentable portion of municipal solid waste from recyclable materials such as glass and steel. The simpler processing of corn stover (dried stalks), on the other hand, resembles the dry-milling of corn, in which a hammer mill reduces the size of the feedstock. Although the bulk of biomass raises handling costs, the conversion of biomass into ethanol is nearly total and eliminates the substantial cost of drying and handling coproducts such as corn gluten feed and dried grains and solubles. Biomass conversion plants, however, lack the flexibility of a wet-milling plant to produce high-fructose corn syrup when not producing ethanol.

Although operating and capital costs for an efficient biomass conversion plant are slightly higher than typical costs for corn-processing plants, feedstock costs may be dramatically lower. Feedstock costs for some wastes that are expensive to dispose of, such as municipal solid waste and yard waste, may even be negative. That is, municipalities may be willing to pay ethanol producers to take the waste. The payments are called tipping fees. The primary cost for most wastes and residues is collection and storage, as well as any necessary pre-plant processing. For example, one estimate of the cost of using corn stalks for ethanol production is 20 cents per gallon of ethanol, including a price for the material, the cost for removing and stacking stalks, and the cost of transportation (Gerber, list of Individuals and Organizations Contacted). Before low feedstock costs are likely to give an advantage to individual biomass conversion plants, however, a steady supply of biomass must be ensured and an infrastructure must be developed for harvesting, storing, and transporting.

Industry Development

Feedstock characteristics account for the greatest differences between the biomass conversion industry and the corn conversion industry. Because biomass is bulkier than corn and the infrastructure for its handling less well developed, biomass conversion plants are initially likely to be small, with a capacity of 10-50 million gallons of ethanol per year. Construction of plants that can convert municipal lawn and yard waste into ethanol may begin in the next 5 years. Corn wet-milling and dry-milling plants may also begin to convert the fiber portions of their feed coproducts into ethanol, depending on the value of the new, higher quality coproduct. Plants to convert municipal solid wastes and agricultural residues into ethanol would also emerge in the longer run. The variety of biomass feedstocks and small size of conversion plants should involve a wider variety of participants than in the corn ethanol industry, including local governments, farmer cooperatives, and small businesses. Marketing ethanol will be more difficult at this smaller level, but lower production costs may afford openings to these firms.

Conclusions

Technological innovations in converting corn to ethanol will likely lower all three components of production costs: feedstock, operating, and capital costs. In the near term, the adoption of innovations in new facilities will result in lower equipment costs, lower ingredient costs, and slight ethanol yield increases over current plants. Cost reductions of 5-7 cents per gallon are likely in the near term (by 1996). Older plants, having already invested in equipment, will be unable to take full advantage of capital cost savings, but can still save 3.5-5 cents per gallon.

In the long term (by 2001), a state-of-the-art corn conversion plant could reduce costs further by improving fermentation processes and converting a portion of its coproducts into ethanol through the conversion of corn fiber. Adding these technologies to a new plant will increase cost savings to 9-15 cents per gallon (7- to 11-percent savings over the cost of production in a current state-of-the-art plant). The innovations discussed in this report apply to most of the steps in the production process where significant savings are possible. Additional cost savings may result from incremental improvements to production efficiency or unexpected breakthroughs, but are likely to be small relative to the projected savings, especially in the near term.

The cost of producing ethanol will also be greatly influenced by technological advances other than innovations in the plant. Farm technologies that raise corn yields or lower input costs may lower feedstock costs for ethanol production. Refinements and new, higher value uses for coproducts are an even likelier source of new revenues for producers and could reduce the cost of ethanol by as much as plant innovations.

By the turn of the century, biomass-derived ethanol may begin to complement ethanol derived from corn. The conversion of biomass into ethanol greatly increases the supply and variety of feedstocks available for ethanol production. Operating and capital costs for biomass conversion plants are comparable to combined costs at corn conversion plants. Feedstock costs can be distinctly lower. Technical barriers to economical biomass conversion, however, still exist and lower cost levels may be achieved only after pilot plants are constructed and the production process is refined.

The use of ethanol as a fuel supplements imported oil as a domestic renewable resource with some environmental benefits. Because of the relatively high costs of production, however, the production of ethanol is supported by government incentives. Cost reductions from the new technologies will move the industry somewhat nearer competitiveness without incentives.

Endnotes

1. The energy required to produce 1 gallon of ethanol (43,000 Btu) is less than the energy contained in a gallon of ethanol (78,000 Btu).

2. Hybrid techniques that use elements of both wet- and dry-milling exist and may be used more in the future.

3. Each bushel of corn that enters the wet-milling process yields approximately 13.5 pounds of CGF, 2.65 pounds of CGM, 1.55 pounds of corn oil, and 2.5 gallons of ethanol. The dry-milling process produces an average 17.5 pounds of distiller's dried grains plus solubles (DDGS) and 2.6 gallons of ethanol. Higher ethanol yields are documented in some dry mills, where DDGS yields can be as low as 16 pounds per bushel.

4. The final dehydration can be accomplished through (1) azeotropic distillation using benzene or another azeotrope, (2) a molecular sieve, (3) a corn grits sieve, or (4) pervaporation, the use of a semipermeable membrane.

5. A bushel of corn weighing 56 pounds yields about 34 pounds of starch (Ladisch, 1987; Lawford, 1988). Starch converted to glucose with perfect efficiency would yield approximately 37.4 pounds of fermentable sugar in hydrous form. If the sugars were then fermented with perfect efficiency and all the water removed with no ethanol loss, the result would be about 2.85 gallons of fuel-grade ethanol. If the fiber portion of the kernel were converted as well, an additional 0.3 gallon might be produced. However, industry averages are less than 2.6 gallons of ethanol per bushel of corn.

6. Coproducts from the fermentation of five-carbon sugars, which are present in the hemicellulose portion of grasses, wood fibers, and even corn hulls, afford an even wider range of recoverable coproduct possibilities (Tsao, Ladisch, and Bungay, 1987). Agricultural Research Service scientists estimate that savings of 13-18 cents per gallon are possible through coproduct development in the next 3-5 years.

Individuals and Organizations Contacted

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Robert W. Schwandt, private consultant, Decatur, IL.

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U.S. Department of Agriculture
Economic Research Service

SUMMARY OF REPORT

Restricting Chemical Use on the Most Vulnerable Cotton Acreage Can Protect Water Quality With Only Minor Effects on Cotton Yields and Prices

Number 6, January 1993

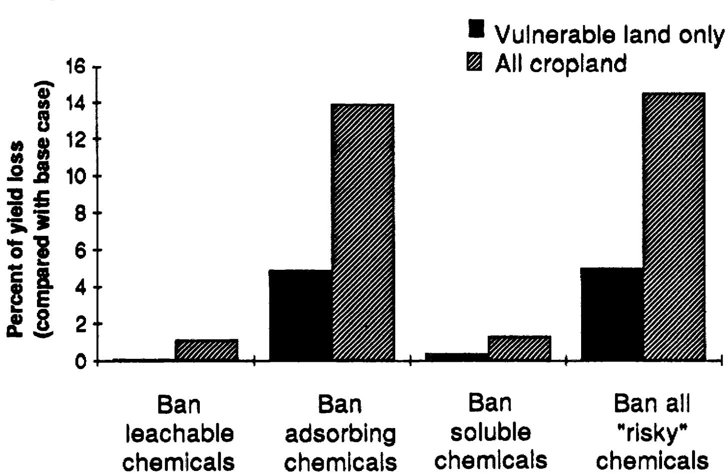
Contact: Stephen R. Crutchfield, (202) 219-0444.

Environmental damage to surface and ground water posed by cotton farming may be reduced, with only limited effects on yields and prices, if restrictions on agrichemical use or production are applied to just those acres most vulnerable to water-quality problems. The most widespread potential damage is from nitrates in fertilizer that can pollute ground water and pesticides that can contaminate surface water.

Production of cotton appears less likely than other crops to cause erosion-induced water-quality problems because cotton acreage is not the major source of cropland erosion in most regions. Widespread restrictions on the use of chemicals likely to leach, dissolve in cropland runoff, or attach to eroding soils may reduce the risk of water-quality degradation, but may also raise cotton prices by reducing yields. These conclusions flow from USDA's 1989 Cotton Water Quality Survey that gathered data on cotton agricultural chemical use and related production practices and resource conditions in 14 cotton States. Data gathered on the use of fertilizers, herbicides, insecticides, and other agricultural chemicals were analyzed to assess the potential water-quality problems that may be associated with cotton production.

Yield losses from chemical restrictions on cotton acreage

Yield losses are minimized if chemical restrictions are targeted to only cotton acreage at greatest water-quality risk.



Widespread Restrictions Could Raise Cotton Prices

The study's results highlight the importance of targeting pollution-prevention programs to attain the most cost-effective environmental protection strategies. Restricting the use of environmentally damaging chemicals on all cotton acreage could reduce the overall potential for water-quality impairment, but could raise cotton prices by as much as 31 percent. More specific chemical-use restrictions, targeted to acreage considered at greatest water-quality risk, could achieve nearly the same level of environmental protection, but would limit price increases and reduce yield losses. Modifying production practices to reduce soil erosion could generate $25 million in economic benefits by reducing sedimentation in surface water systems.

To Order This Report...

The information presented here is excerpted from ***Cotton Production and Water Quality: Economic and Environmental Effects of Pollution Prevention,*** AER-664, by Stephen R. Crutchfield, Marc O. Ribaudo, LeRoy T. Hansen, and Ricardo Quiroga. The cost is $8.00.

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